J-PARC RCS

Effects of $2\nu_x - 2\nu_y = 0$ on injection painting

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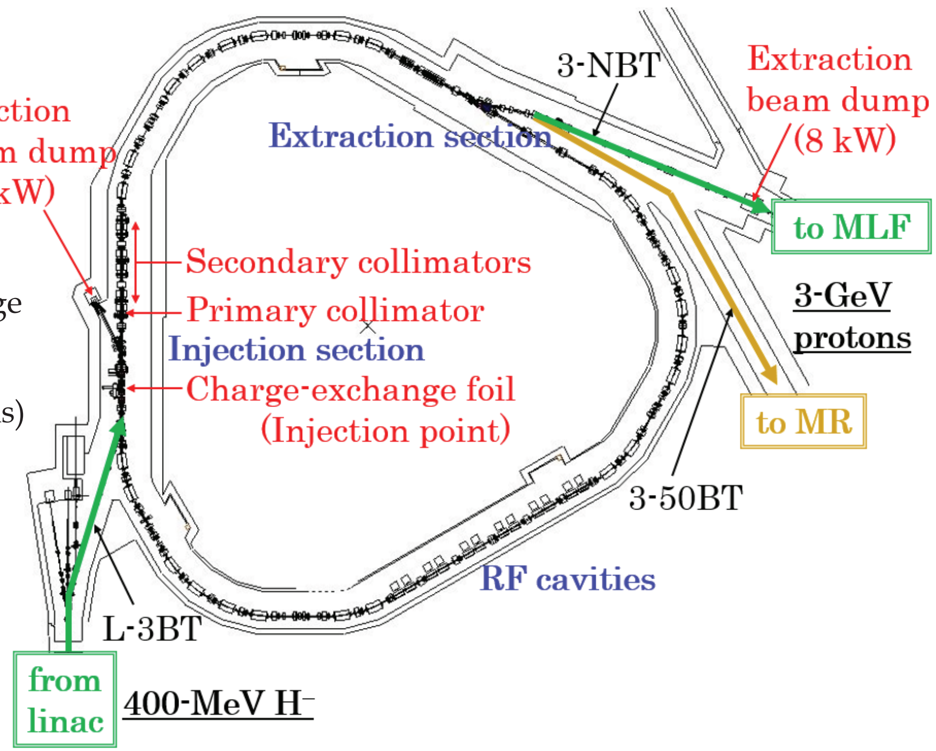
1. Outline of the J-PARC RCS

J-PARC 3-GeV Rapid Cycling Synchrotron (RCS)

Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
Number of bunches	2
Injection	Multi-turn, Charge-exchange
Injection energy	400 MeV
Injection period	0.5 ms (307 turns)
Injection peak current	50 mA
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	8.33×10^{13}
Beam power	**1 MW**

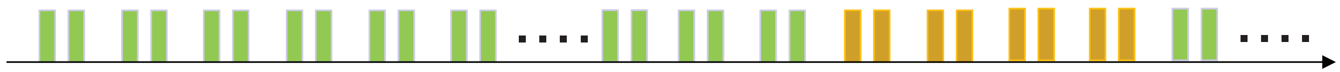


- ✓ RCS has two functions as;
  - **- Proton driver for producing pulsed muon and neutrons at the material and life science experimental facility (MLF)**
  - **- Injector to the 30-GeV main ring (MR)**
- ✓ The requirements for the beam operations to MLF and MR are different. Thus, different parameter optimizations are required for each.

Requirements for the beam operations to MLF & MR

✓ Most of the RCS beam pulses are delivered to MLF,
while only four pulses every several second are injected to MR
by switching the beam destination pulse by pulse.

Destinations of the 25-Hz beam pulses



~95.5% to MLF **~6.5% to MR**

◆ For MLF

✓ Machine activations of RCS are mainly determined by the beam operation to MLF.

⇒ Sufficient beam loss mitigation

✓ To keep a sufficient life-time of the neutron target, a shockwave on the neutron target has to be mitigated.

⇒ Wide-emittance beam with less charge density

⇒ "**Large painting**"

◆ For MR

✓ Beam loss mitigation at MR

⇒ Narrow-emittance beam with less beam halo

⇒ "**Small painting**"

In order to meet the different requirements for MLF and MR, we utilized "**transverse injection painting**".

Transverse injection painting

- Horizontal painting by a horizontal closed orbit variation during injection

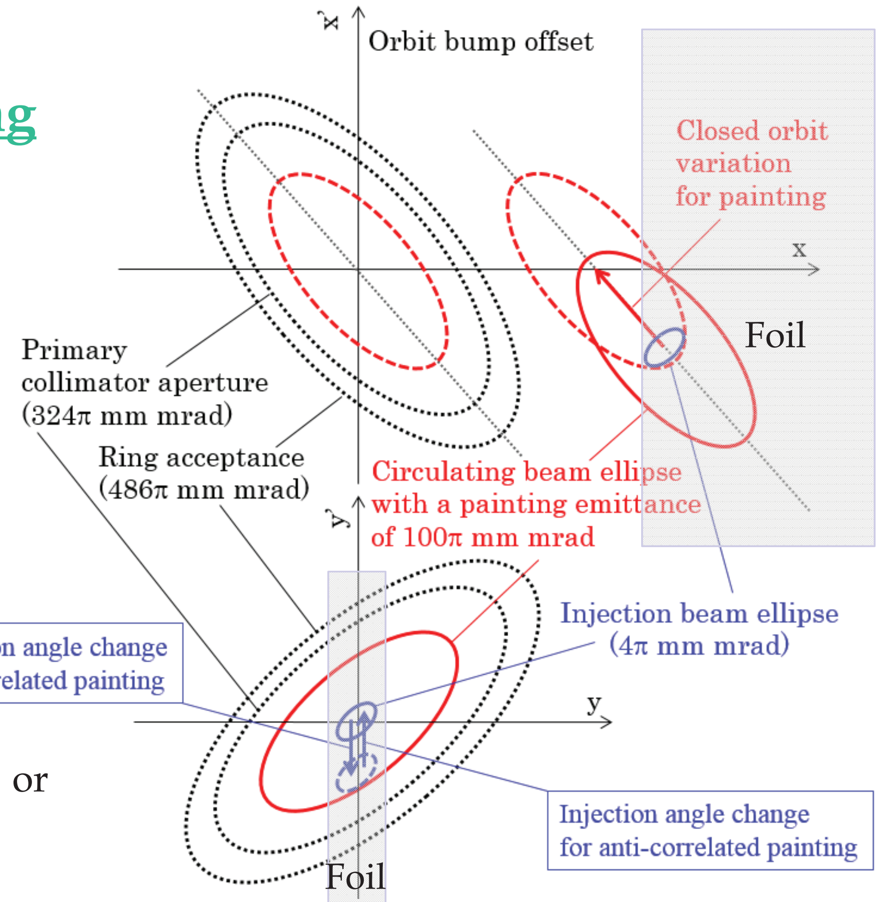
⇒ The injection beam is filled
  - (a) from the middle to the outside

  on the horizontal phase space.

- Vertical painting by a vertical injection angle change during injection

⇒ The injection beam is filled
  - (b) from the middle to the outside, or
  - (c) from the outside to the middle

  on the vertical phase space.



(a)+(b) ⇒ Correlated painting

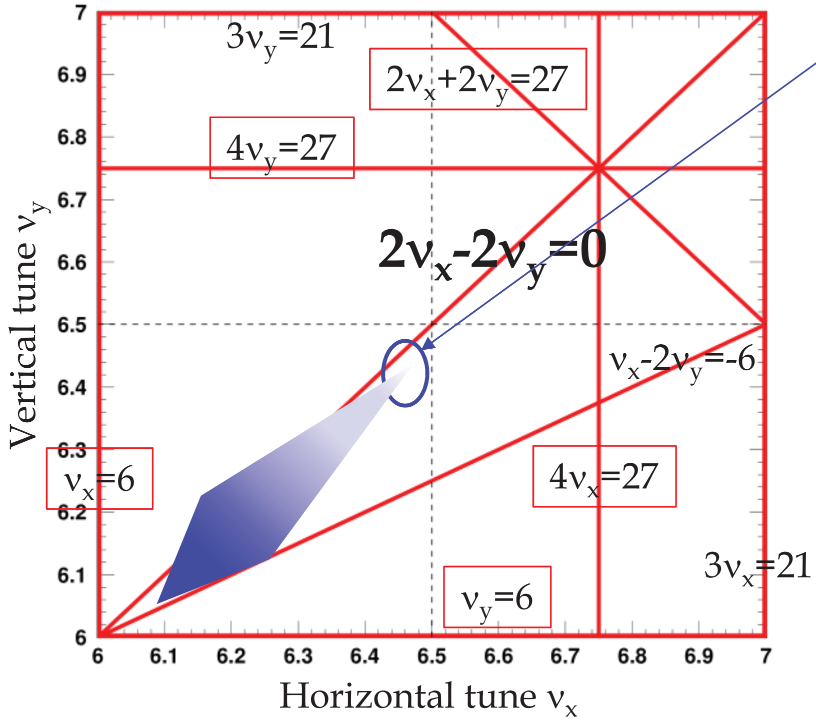
(a)+(c) ⇒ Anti-correlated painting

Painting emittance; ε_{tp}=0~216π mm mrad

✓ We optimized injection painting to meet the requirements for MLF and MR.
- Better selection of correlated and anti-correlated painting
- Optimization of the painting emittance

Tune diagram near the operational point

— Systematic resonances up to 4th order derived from the 3-fold symmetric lattice of RCS



Operational point:
(6.45, 6.42)
･･･allowing tune shifts to avoid serious resonances:
$\nu_{x,y}$=6, $4\nu_{x,y}$=27, $2\nu_x+2\nu_y$=27

✓ The point is very close to $2\nu_x-2\nu_y$=0.

✓ The $2\nu_x-2\nu_y$=0 resonance is not so serious, not leading to serious emittance growth, but it causes emittance exchange.

✓ The emittance exchange has a major influence on the formation of the beam distribution during injection painting.

The main topic of this talk is to discuss:

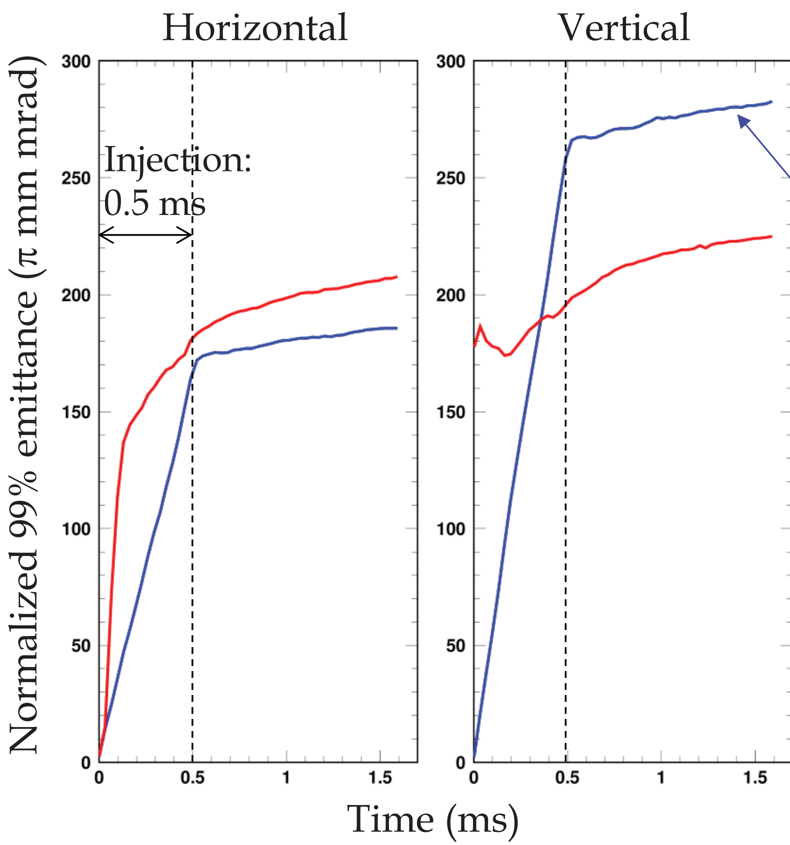
- Influence of the emittance exchange on injection painting
- Optimization of the painting method in such a situation involving the emittance exchange

for a high-intensity beam (~8.33 x 10^{13} ppp: ~1 MW-eq.).

2.1 Particle motions during injection painting with a large painting emittance of ε_{tp}~200π mm mrad

. . . required for the beam operation to MLF

Time dependence of the beam emittance



ε_{tp}=200π mm mrad

— Correlated painting

— Anti-correlated painting

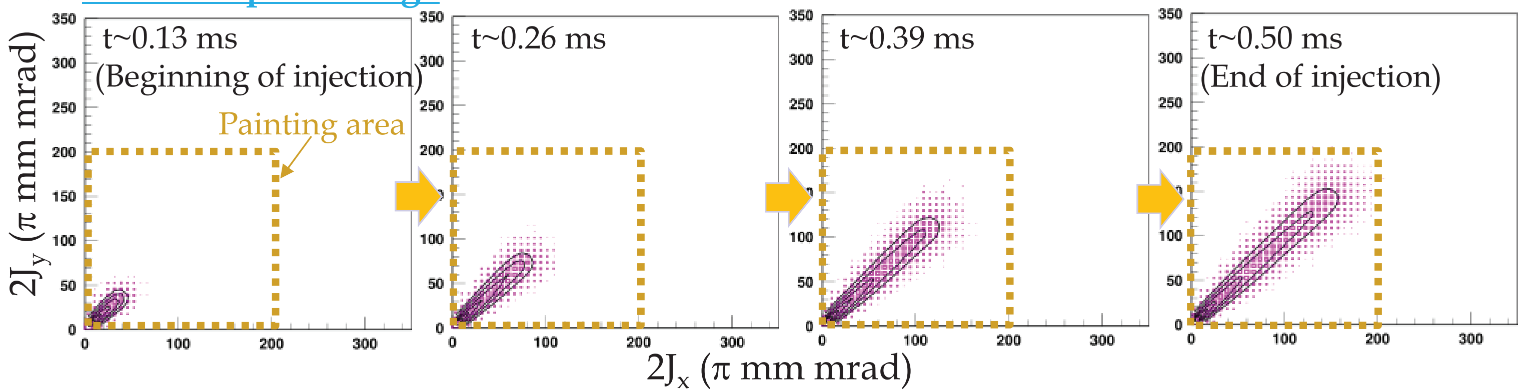
✓ A large emittance growth occurs for correlated painting, making a significant beam loss.

✓ The mechanism of this emittance growth can be understood by considering the effect of the emittance exchange.

Betatron actions (J_x, J_y) during injection

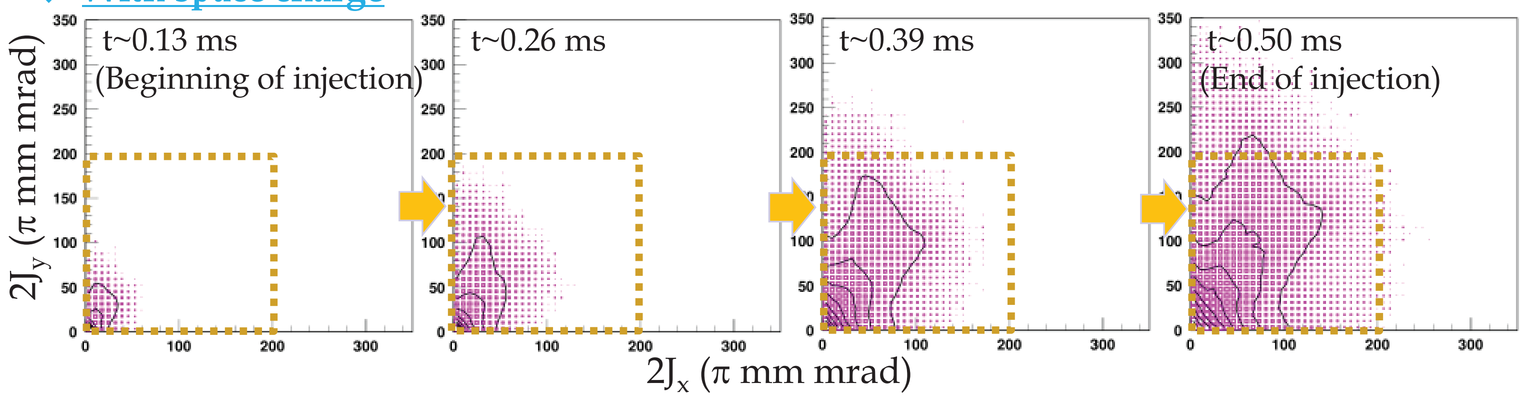
Correlated painting of ε_{tp}=200π mm mrad

◆ Without space charge



✓ The above situation significantly changes when the space charge is turned on.

◆ With space charge

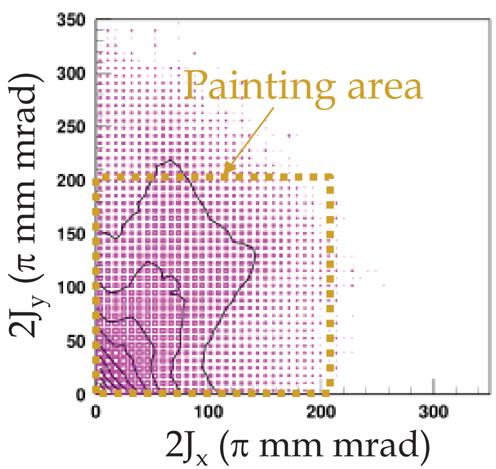


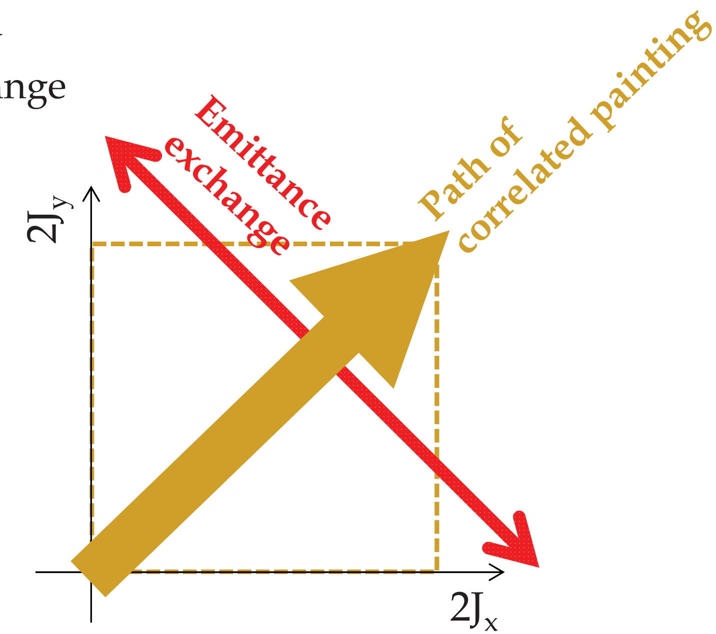
✓ We can see a diffusion of particles swerving from the path of beam painting, and it finally causes emittance growth over the painting area.

Effect of the emittance exchange in correlated painting

Correlated painting of ε_{tp}=200π mm mrad

✓ The emittance dilution is mainly led through the emittance exchange caused by $2\nu_x$-$2\nu_y$=0.



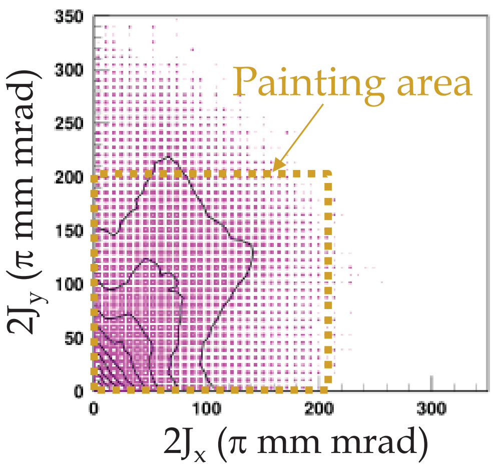


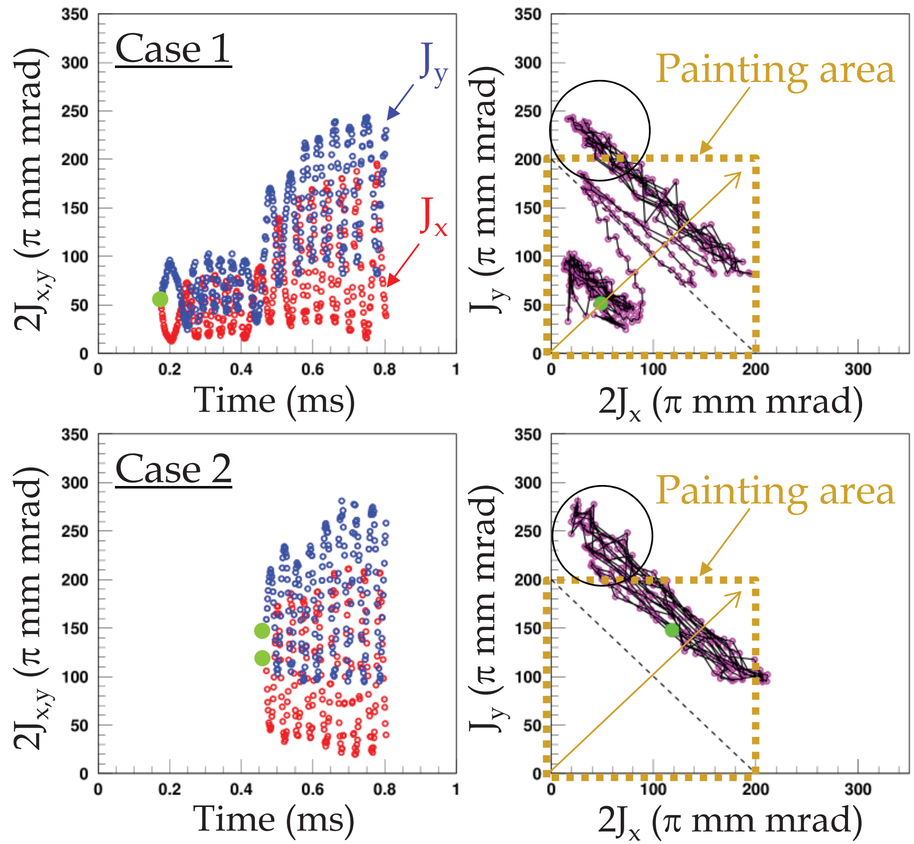
✓ The emittance exchange occurs in the orthogonal direction to the direction of correlated painting.

⇒ The emittance exchange is more directly connected to significant emittance growth.

Single-particle motion of one macro-particle leading to large emittance growth

Correlated painting of ε_{tp}=200π mm mrad

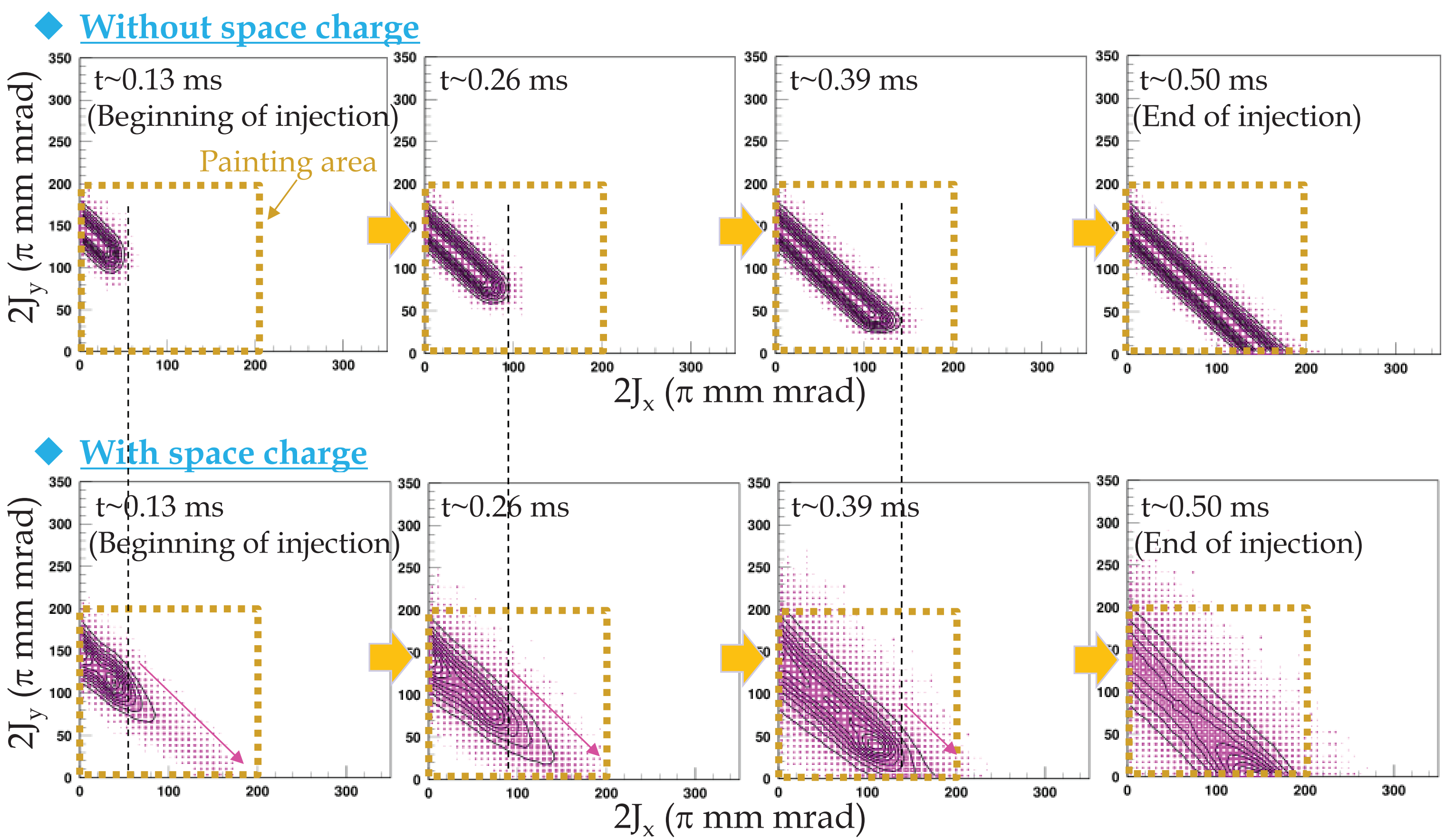




- ✓ This figure clearly shows the emittance growth is mainly caused by the emittance exchange which occurs perpendicularly to the path of beam painting.
- ✓ This is the main reason why a large emittance growth occurs for correlated painting.

Betatron actions (J_x, J_y) during injection

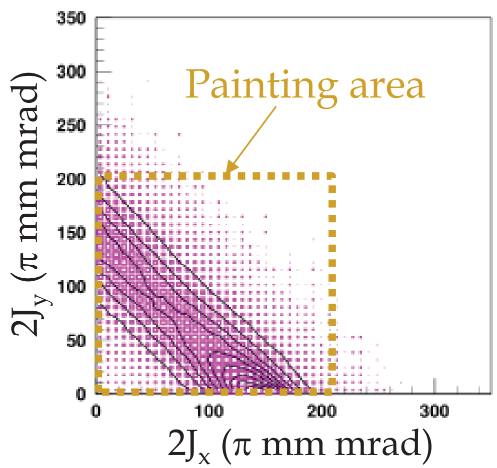
Anti-correlated painting of ε_{tp}=200π mm mrad

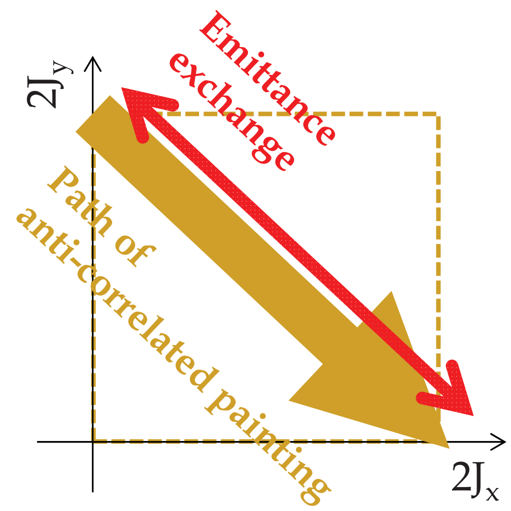


✓ We can find the emittance exchange occurs along the path of beam painting, when the space-charge is turned on.

Effect of the emittance exchange in anti-correlated painting

Anti-correlated painting of ε_{tp}=200π mm mrad



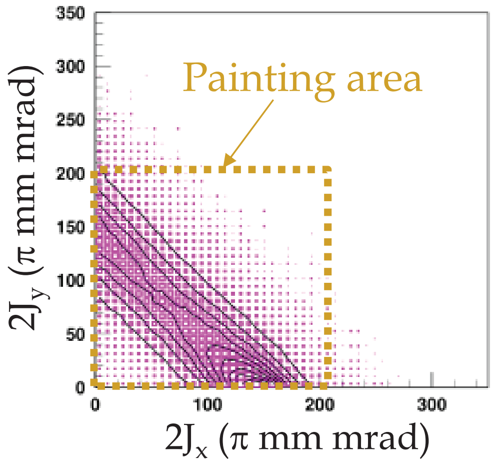


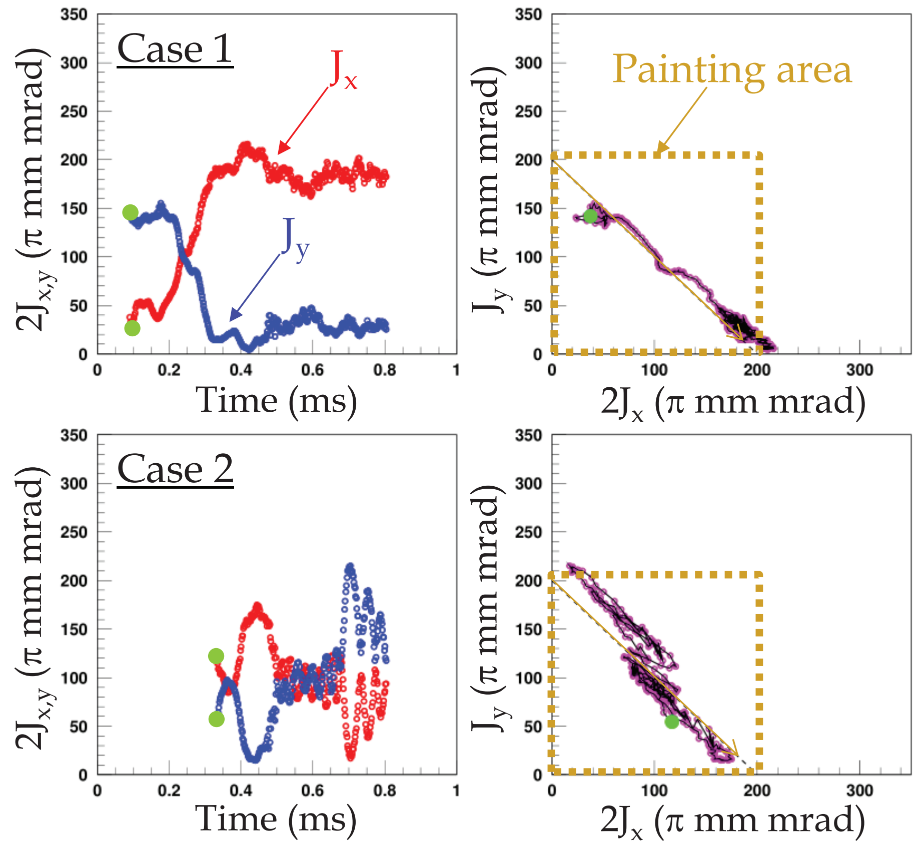
✓ In anti-correlated painting,
the direction of the emittance exchange is the same
as the direction of the beam painting.

⇒ This geometrical situation prevents the emittance exchange
from causing a large emittance growth.

Single-particle motion of one macro-particle

Anti-correlated painting of ε_{tp}=200π mm mrad

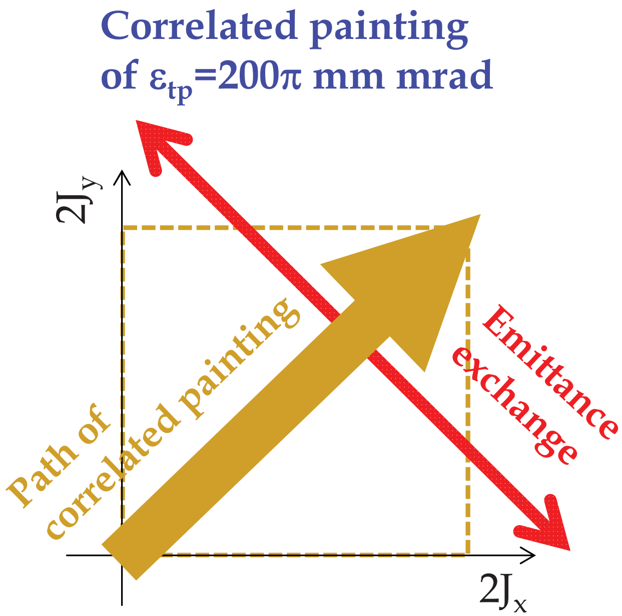


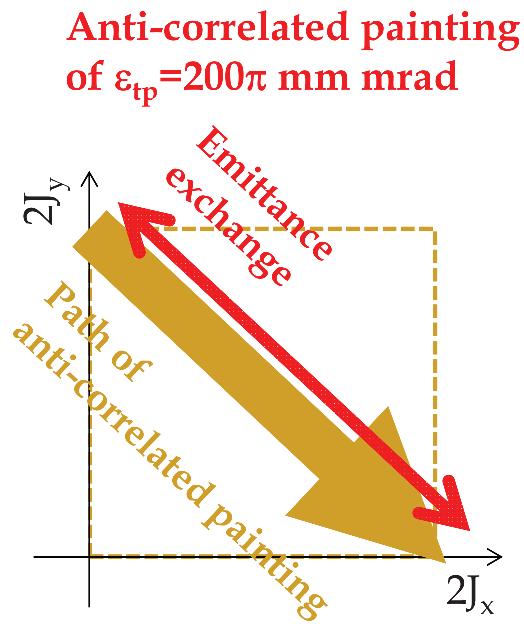


✓ The direction of the emittance exchange is the same as the direction of the beam painting.

⇒ Most of the beam particles stay in the painting area even if the emittance exchange occurs.

Correlated painting vs anti-correlated painting



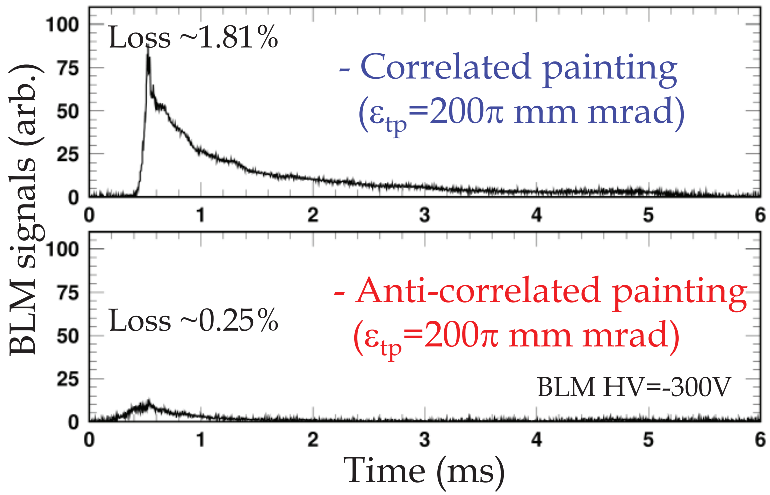


- ✓ The emittance exchange has different effects on the formation of the beam distribution depending on the geometrical relation with the path of the beam painting in the (J_x, J_y) space.
- ✓ Emittance growth caused by the emittance exchange is more enhanced for correlated painting, while it is well suppressed for anti-correlated painting.

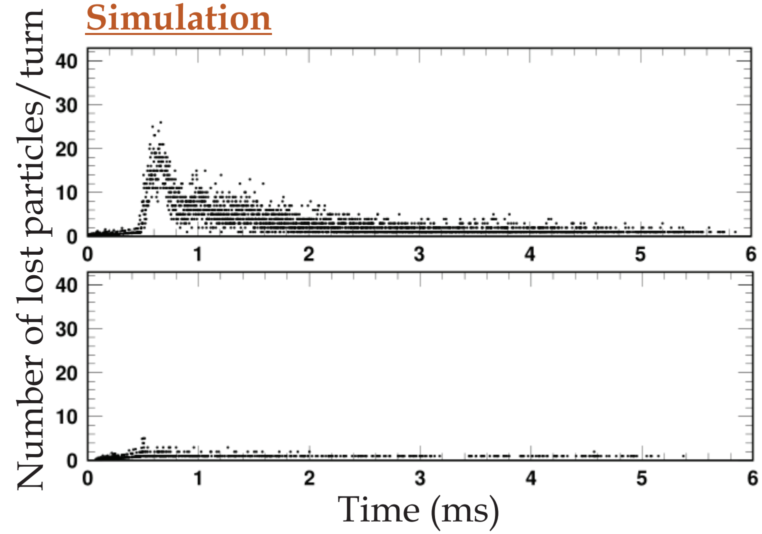
Beam loss at the collimator

✓ The above analysis concludes that anti-correlated painting is less affected by the emittance exchange; it more favors the suppression of emittance growth caused by the emittance exchange.

Measurement **1-MW beam test**



Simulation



✓ Through the measurements and numerical simulations, we confirmed the advantage of anti-correlated painting.

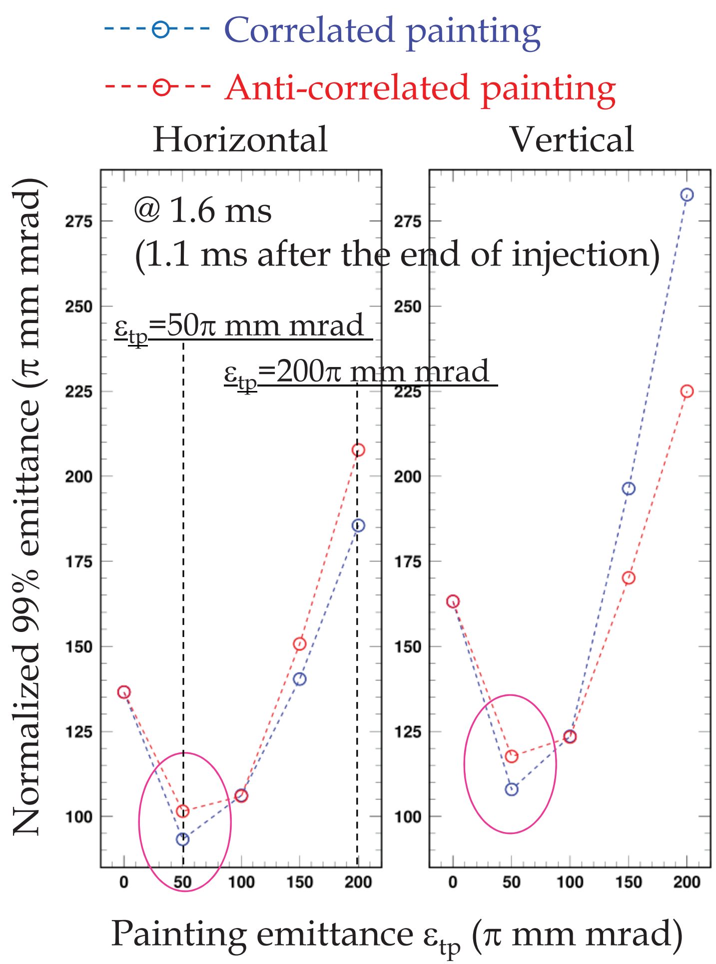
✓ Note that the conclusion obtained here is just for the case of large painting.

✓ We next investigated the case of small painting.

Particle motion during injection painting with a small painting emittance of ε_{tp}~50π mm mrad

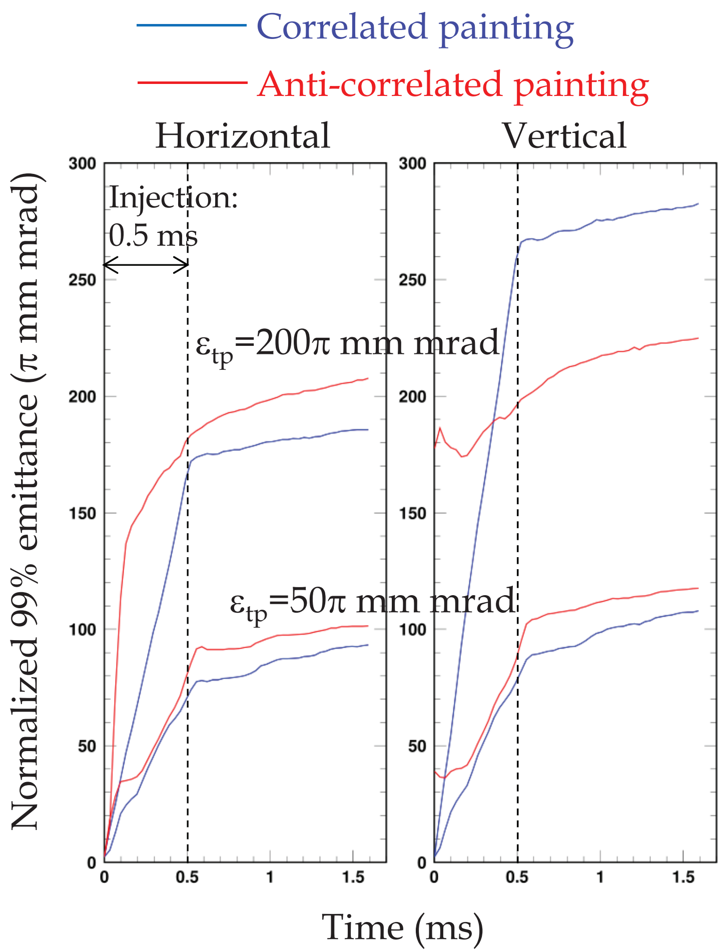
. . . required for the beam operation to MR

Beam emittance as a function of the painting emittance



- ✓ This dependence is ascribed to the balance between the painting emittance and its resultant space-charge mitigation.
- ✓ The minimum beam emittance is achieved for a small painting emittance of ε_{tp}=50π mm mrad.
- ✓ Correlated painting rather than anti-correlated painting provides narrower beam emittance at ε_{tp}=50π mm mrad.
- ✓ This situation for correlated and anti-correlated painting is completely opposite to the case of large painting.

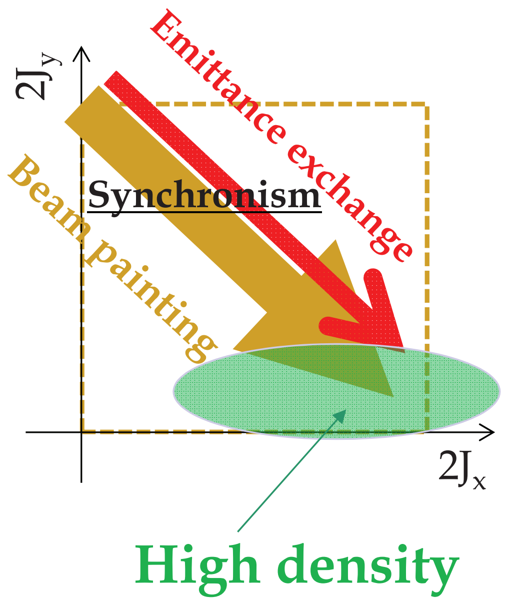
Time dependence of the beam emittance: large painting vs small painting



- ✓ In case of large painting, anti-correlated painting gives less emittance growth.
- ✓ But, in case of small painting, correlated painting rather than anti-correlated painting gives narrower beam emittance, contrary to the large painting case.
- ✓ We investigated the cause of this opposite phenomenon observed in small painting.

Effect of the emittance exchange in anti-correlated painting

Anti-correlated painting of ε_{tp}=50π mm mrad



✓ The direction of the beam painting is the same as the direction of the emittance exchange.

⇒ The additional emittance growth caused by the direct effect of the emittance exchange can well be suppressed.

✓ But, this geometrical situation has a potential of causing a significant charge density modulation.

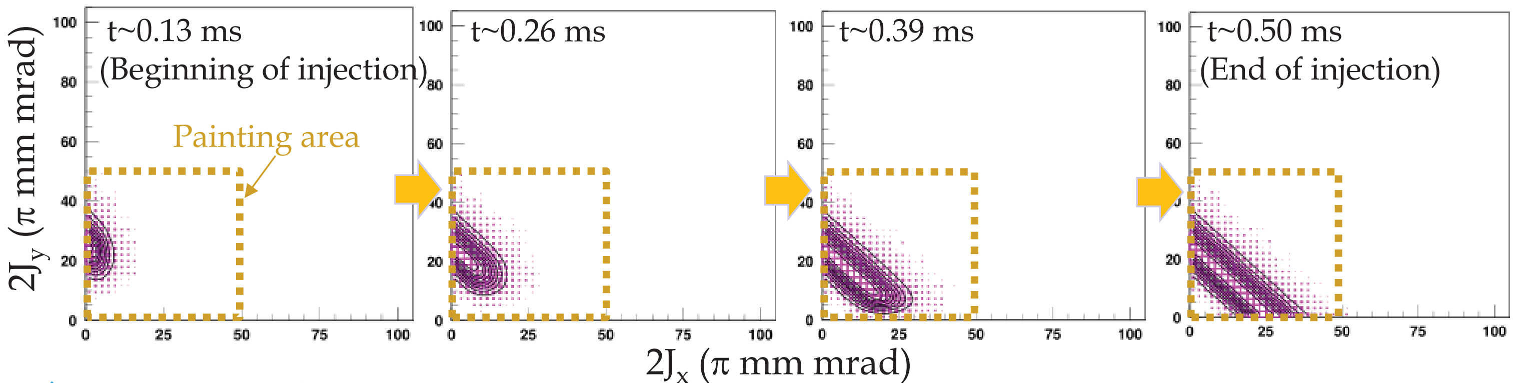
⇒ **The synchronism** between
- **Move of the charge distribution by the emittance exchange** &
- **Beam painting**

possibly makes a **high-density structure**.

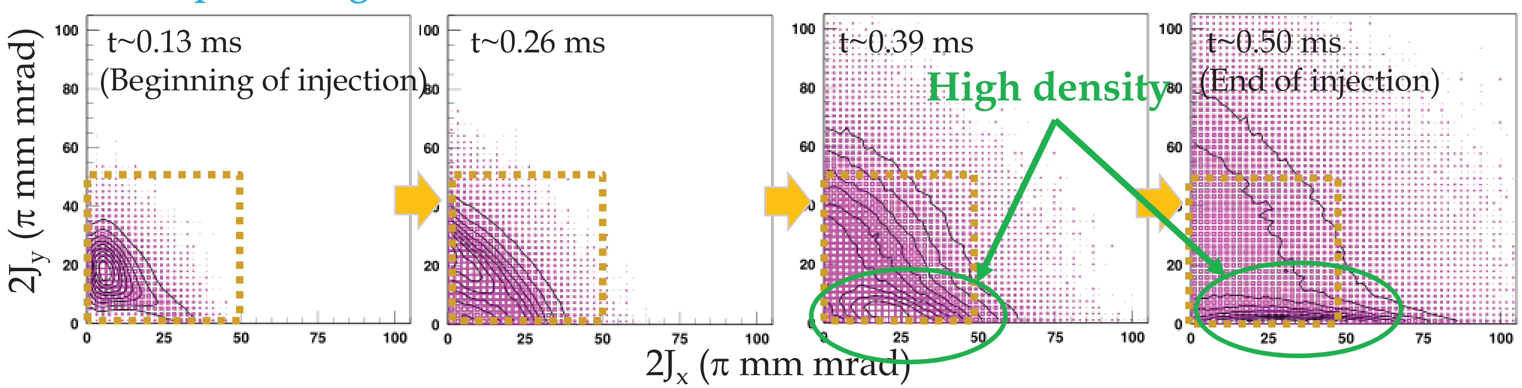
Betatron actions (J_x, J_y) during injection

Anti-correlated painting of ε_{tp}=50π mm mrad

- **Without space charge**



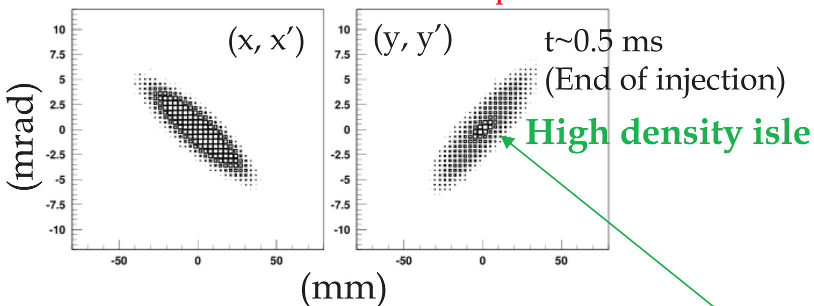
- **With space charge**



- ✓ We can actually find the formation of a high density structure at the late stage of injection.
- ✓ But such a significant charge density modulation is not found in case of large painting. . . . . Why?

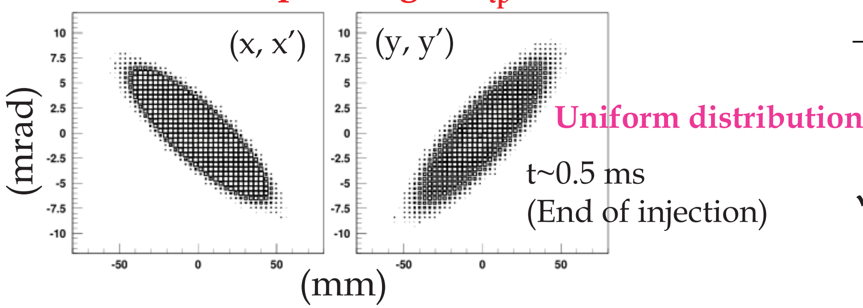
Charge distributions formed by anti-correlated painting: small painting vs large painting

- **Anti-correlated painting of ε_{tp}=50π mm mrad**

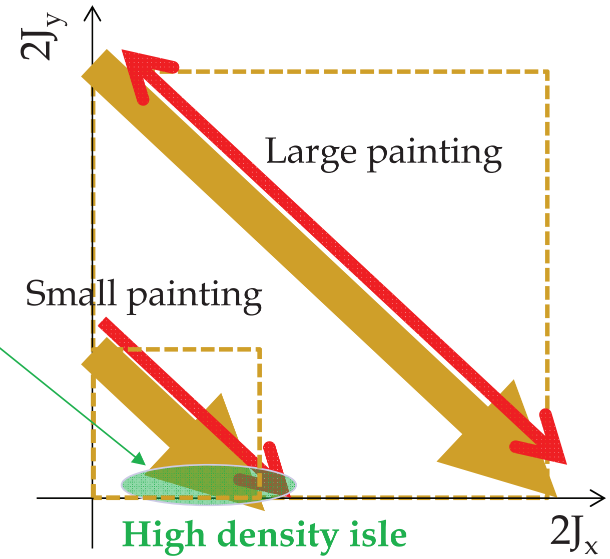


✓ A significant charge density modulation is formed by the synchronism between the beam painting and the emittance exchange.

- **Anti-correlated painting of ε_{tp}=200π mm mrad**



✓ The range of the beam painting is very wider, so the synchronism between the beam painting and the emittance exchange is relatively lost in going to larger painting.

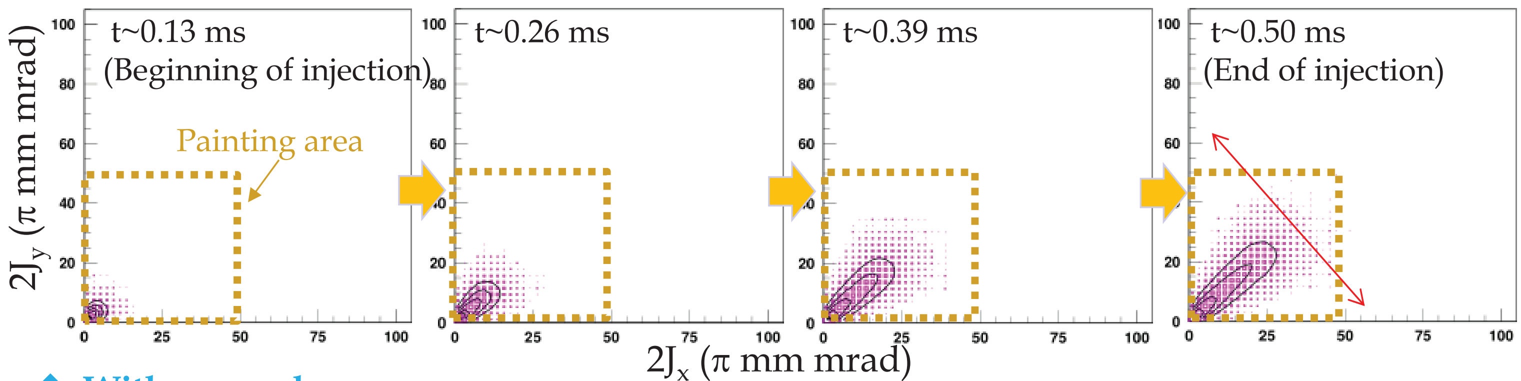


✓ The charge density modulation is a characteristic phenomenon enhanced in anti-correlated painting with a small painting emittance.

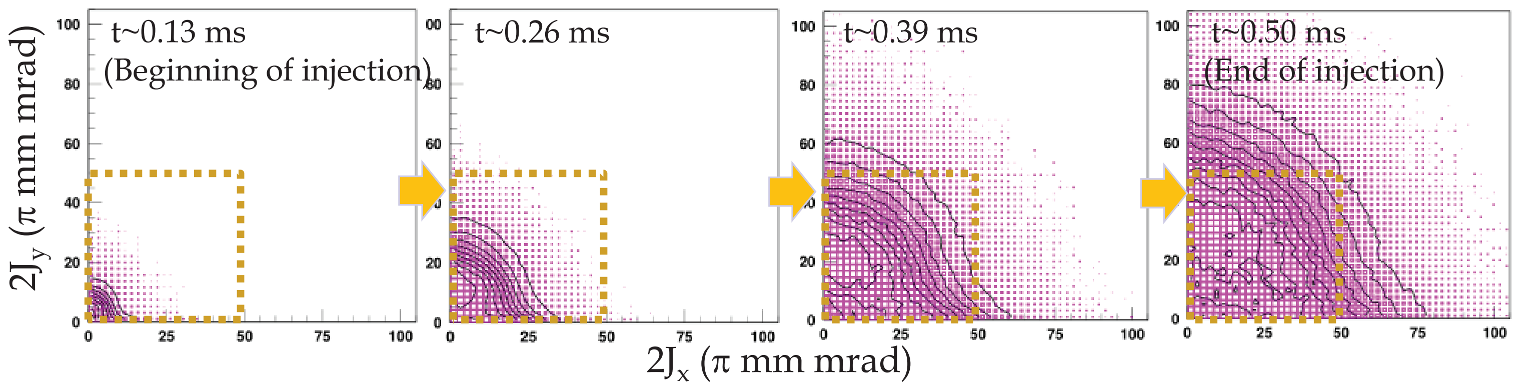
Betatron actions (J_x, J_y) during injection

Correlated painting of ε_{tp}=50π mm mrad

- Without space charge



- With space charge

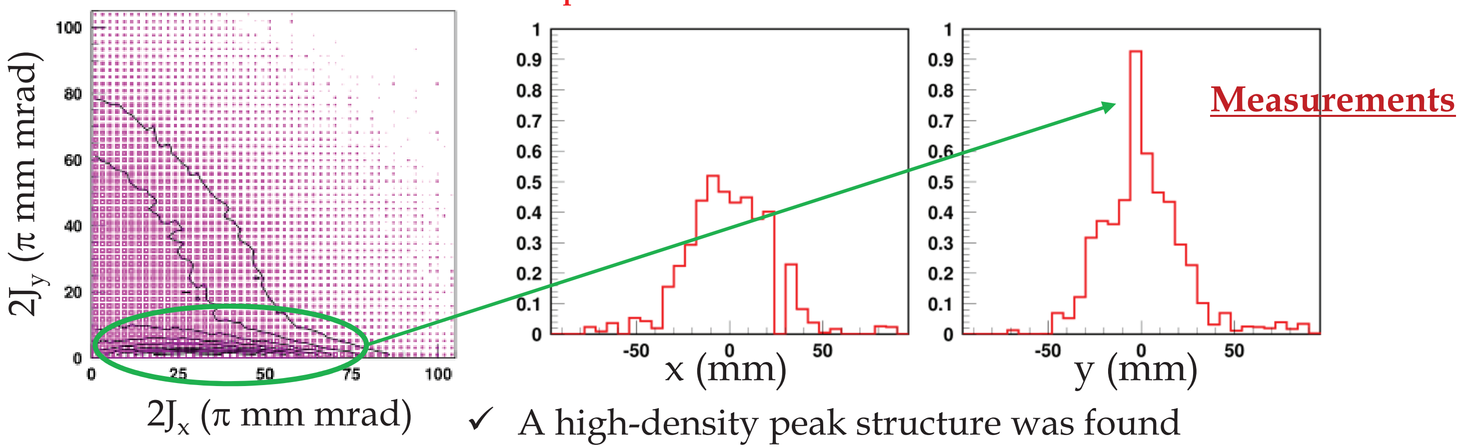


✓ Correlated painting suffers significant emittance growth directly caused by the emittance exchange itself, but it has the advantage of avoiding the charge density modulation; uniform distribution is maintained at all times during injection.

✓ These characteristic particle motions in small painting were experimentally confirmed.

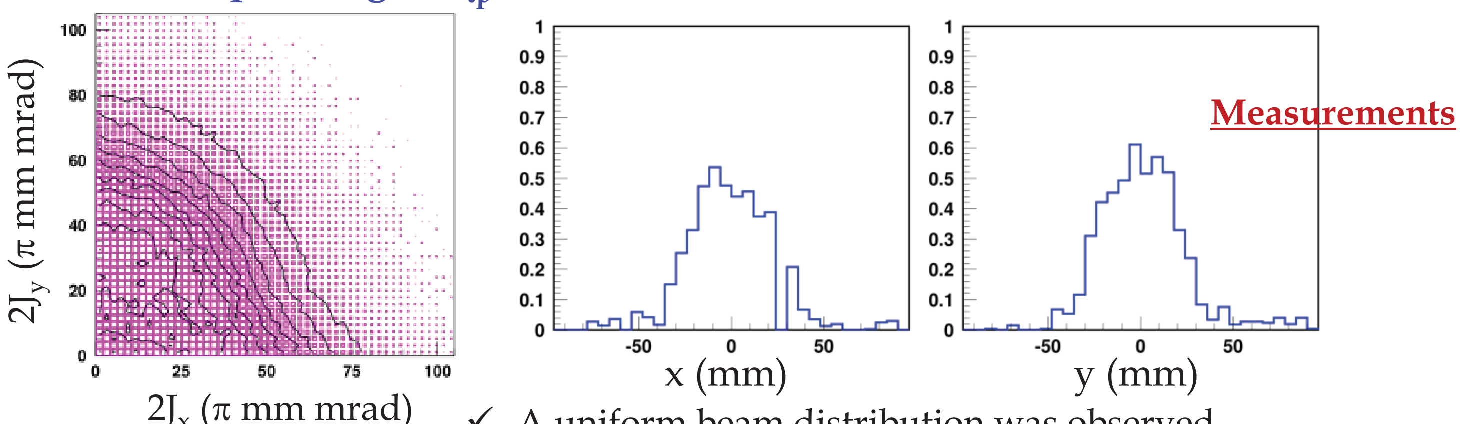
Beam profiles measured at the end of injection

Anti-correlated painting of ε_{tp}=50π mm mrad



✓ A high-density peak structure was found for anti-correlated painting, as predicted.

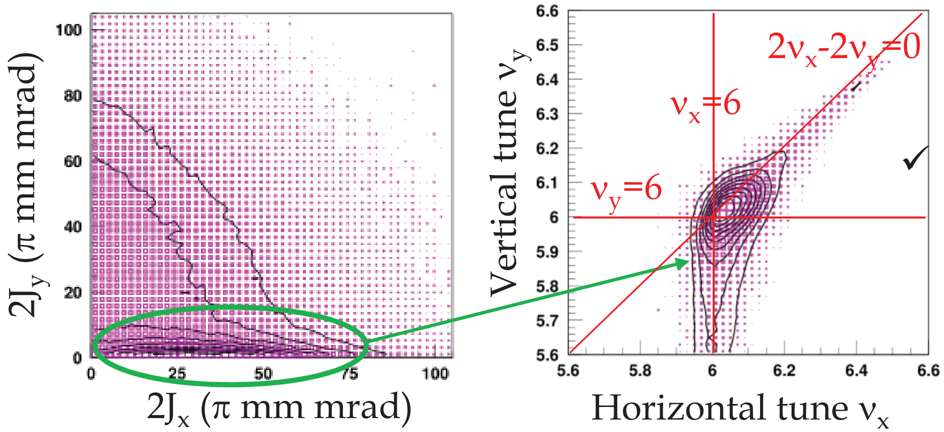
Correlated painting of ε_{tp}=50π mm mrad



✓ A uniform beam distribution was observed for correlated painting, as expected.

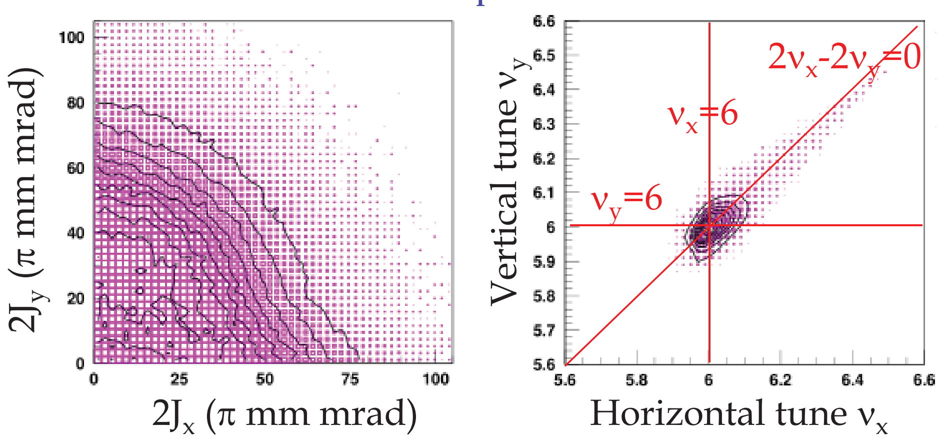
Space-charge detuning

Anti-correlated painting of ε_{tp}=50π mm mrad



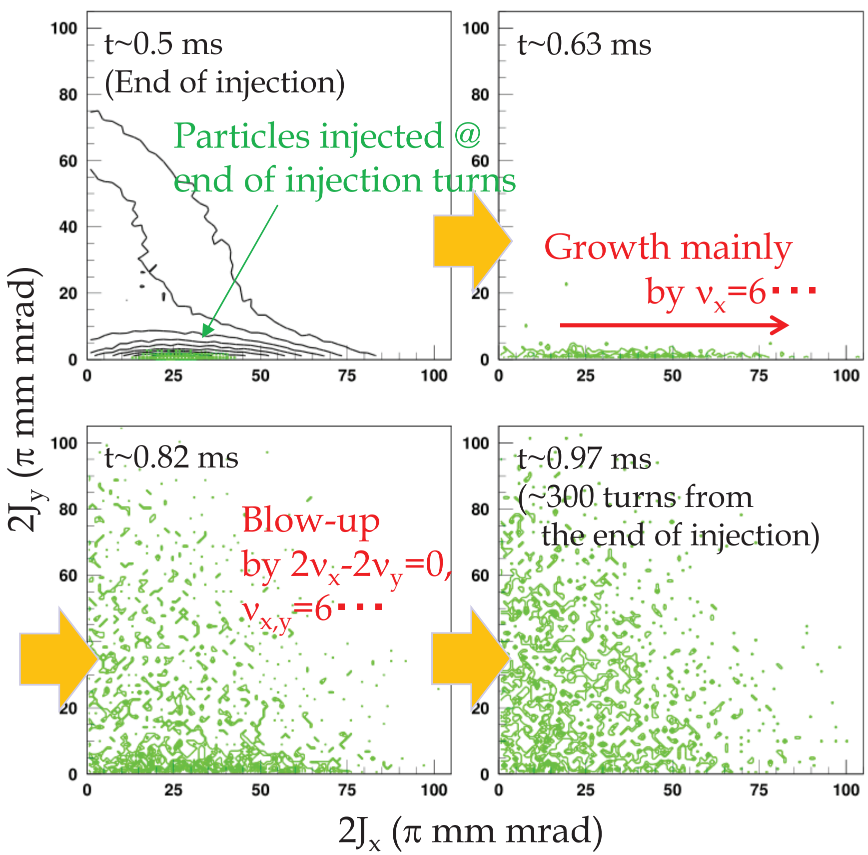
✓ The high-density isle formed in anti-correlated painting causes a large space-charge detuning, leading to a significant additional emittance growth afterward.

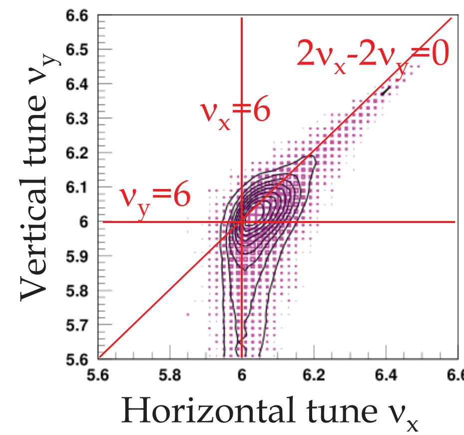
Correlated painting of ε_{tp}=50π mm mrad



Subsequent behavior of the beam particles forming the high-density isle

Anti-correlated painting of ε_{tp}=50π mm mrad





✓ The particles forming the high-density isle diffuse quickly for just 300 turns.

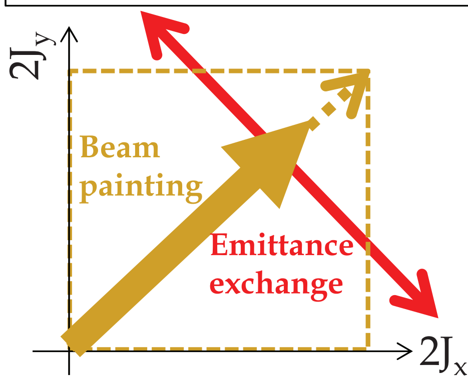
✓ The emittance growth caused via the formation of the high-density isle in the anti-correlated painting is more significant than that directly caused by the emittance exchange itself in the correlated painting.

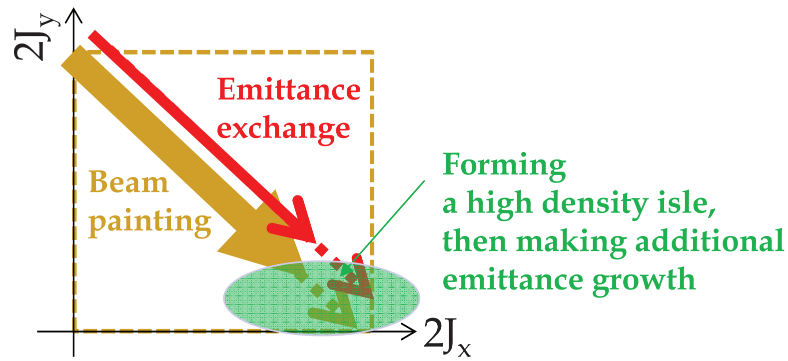
✓ This is the main reason why the anti-correlated painting leads to larger emittance growths in case of small painting.

Result of the discussion

The emittance exchange makes two major effects (A) & (B).

(A) Emittance growth simply caused by the emittance exchange itself, which is more enhanced for correlated paining	(B) Emittance growth caused by the secondary effect of the emittance exchange, namely, through a modulation of the charge density, which is more enhanced for anti-correlated painting



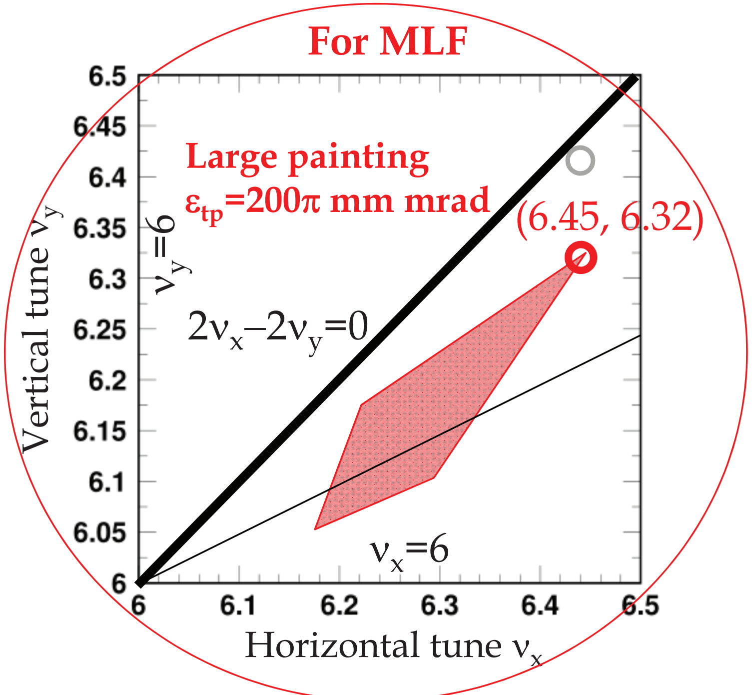


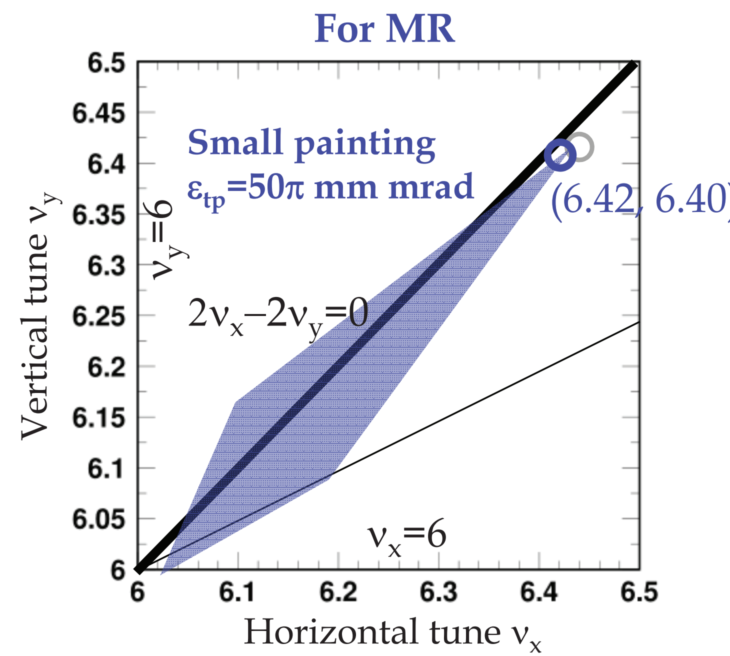
- **Large painting**
  - ✓ The effect (A) is more significant.
  - ✓ Anti-correlated painting, avoiding (A), gives less beam loss.
- **Small painting**
  - ✓ The effect (B) is more significant.
  - ✓ Correlated painting, avoiding (B), leads to narrower beam emittance.

✓ Based on this result, we optimized transverse painting for MLF and MR.

3. Present status and perspective of the J-PARC RCS beam operation

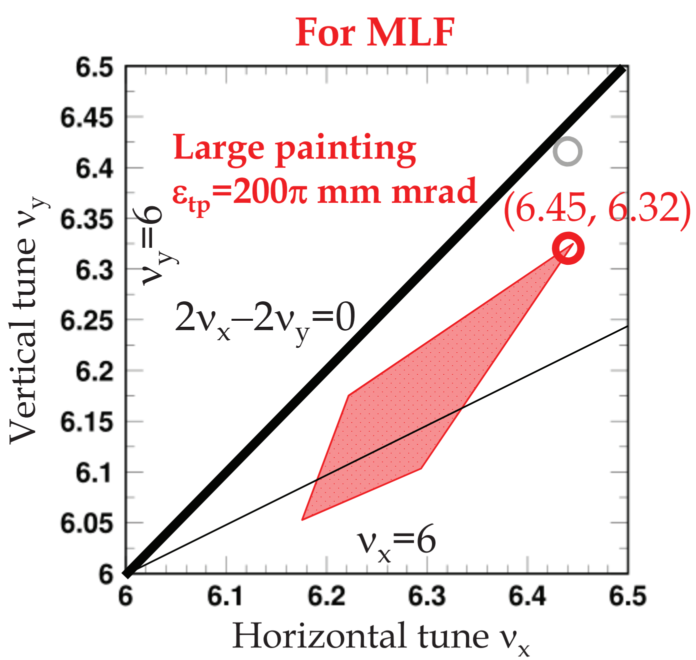
Present operational points used for the beam operations to MLF and MR

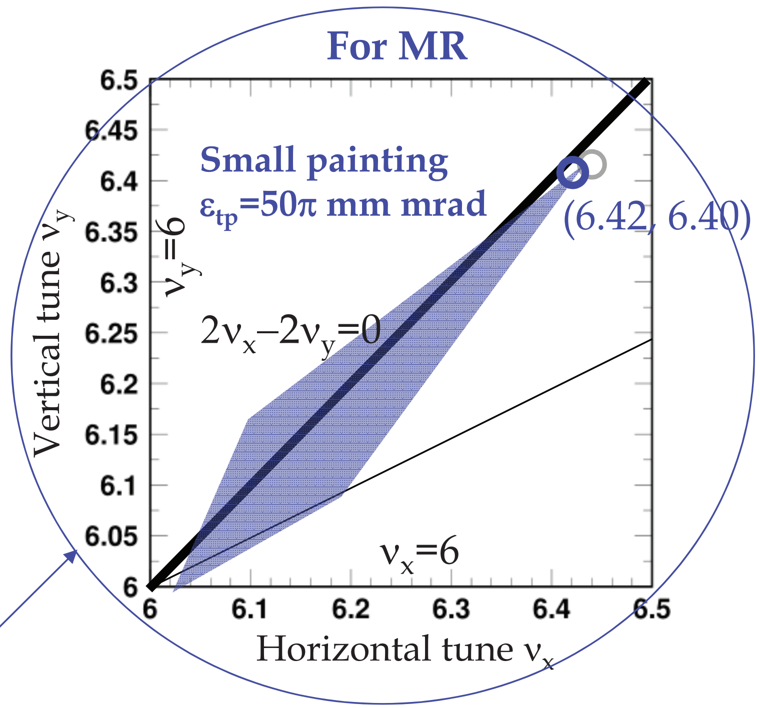




- ✓ The operational point is relatively far from $2\nu_x-2\nu_y=0$; the effect of the emittance exchange is not significant.
- ✓ Correlated painting as well as anti-correlated painting are now feasible for MLF.

Present operational points used for the beam operations to MLF and MR





- ✓ The operational point provides a larger separation from ν=6, but is very close to $2\nu_x-2\nu_y=0$; it minimizes the effects of ν=6, but suffers significant effects of $2\nu_x-2\nu_y=0$.
- ✓ Correlated painting is now applied for MR; correlated painting more favors the suppression of the emittance growth originating from the emittance exchange in case of small painting.

Pulse-by-pulse switching of the operational parameters

- ✓ The operational parameters optimized for the beam operations to MLF and MR are different.

	For MLF	For MR
Lattice tune	(6.45, 6.32)	(6.42, 6.40)
Painting area ε_{tp}	200π mm mrad	50π mm mrad
Painting type	Correlated/ Ani-correlated	Correlated

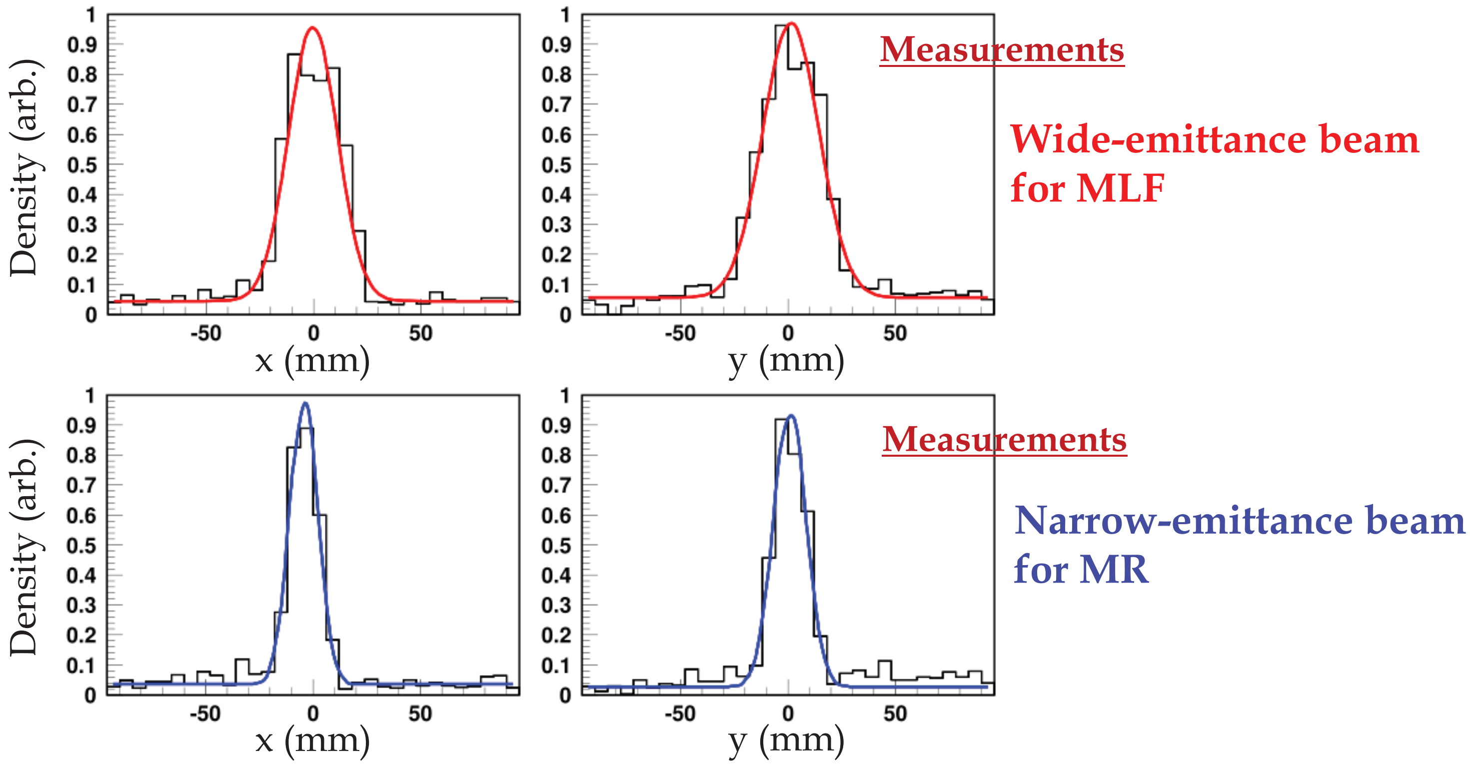
Pulse-by-pulse switching
according as the beam destination, MLF & MR

- ✓ The pulse-by-pulse switching of the betatron tune is conducted with 6 sets of pulsed trim-quadrupole magnets.

- ✓ The pulse-by-pulse switching of the injection painting is performed with 6 sets of pulsed injection bump magnets.

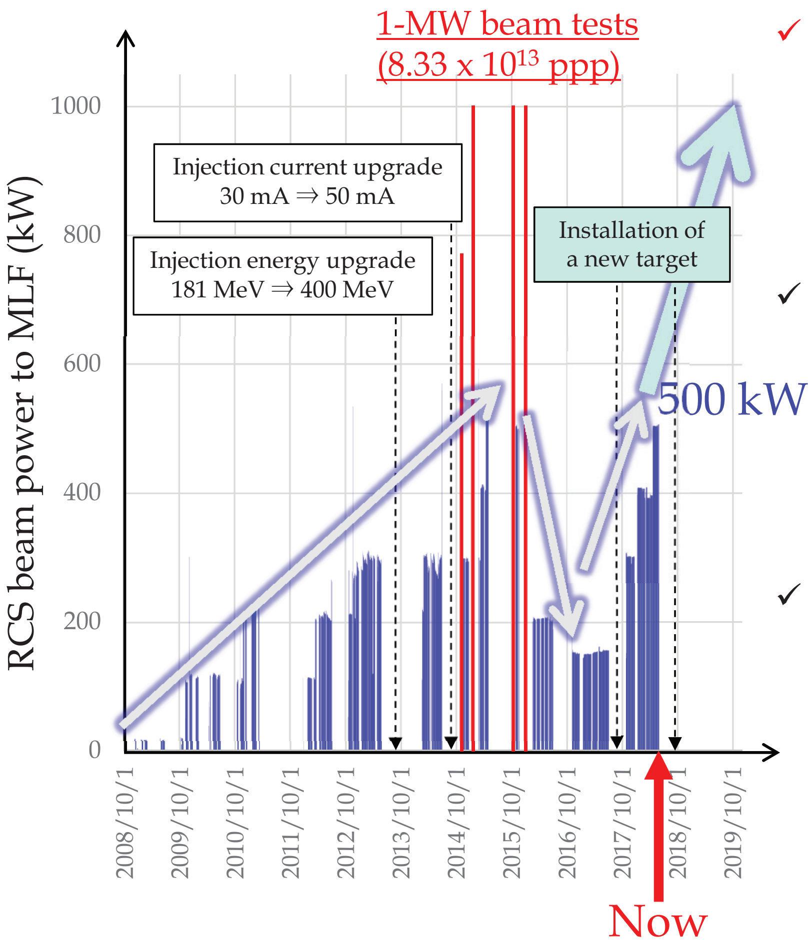
Beam profiles measured at extraction

- ✓ By these series of efforts, we successfully met the requirements for MLF and MR while keeping beam loss within acceptable levels.



- ✓ A wide-emittance beam for MLF and a narrow-emittance beam for MR were successfully achieved as requested.

RCS beam power ramp-up history for the MLF users



- ✓ We have already achieved the 1-MW beam test successfully with a very small beam loss of a couple of 10^{-3}.

  ⇒ The accelerator itself is now ready to try a continuous 1-MW beam operation to MLF.

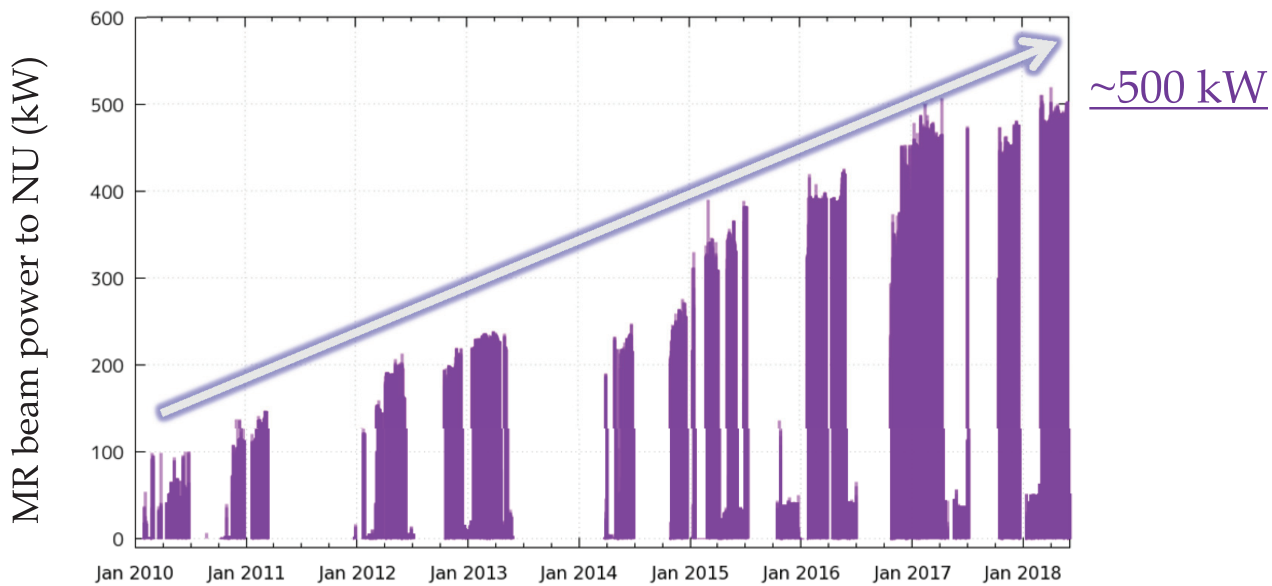
- ✓ But, we had a trouble in the neutron target at the 500-kW beam power; a water leak from the target vessel happened two times one after another in 2015-2016.

  ⇒ Since then, the output beam power for MLF had been limited to ~150 kW.

- ✓ In the last summer maintenance period, a new robust target was installed.

  ⇒ Now we are back to the beam power ramp-up phase again; the beam power is now recovered to 500 kW, and it will be increased step by step to 1 MW from now on, carefully monitoring the condition of the target.

MR beam power ramp-up history for the NU users



- ✓ The RCS is now delivering the beam to MR at the beam intensity of ~6.5 x 10^{13} ppp, corresponding to ~78% of the RCS design beam intensity.
- ✓ With this RCS beam, the MR has recently achieved a new record of a 500-kW beam power via the recent efforts for beam loss reduction including the improvement of the RCS beam quality.
- ✓ The design beam power of MR is 750 kW. To achieve this and more, the MR operation cycle time will be reduced from 2.48 s to 1.3 s.
- ✓ Hardware upgrades to get such a rapid operation cycle, such as the upgrade of the main magnet power supplies, are in progress now.

Summary

- The effects of the emittance exchange on injection painting were investigated for a 1-MW-equivalent high-intensity beam.

- In this work, we found the emittance exchange makes two major effects during injection painting.
  (i) Emittance growth directly caused by the emittance exchange itself
  (ii) Emittance growth caused by the secondary effect of the emittance exchange, namely, via a modulation of the charge density.

- They each are enhanced or mitigated depending on the choice of correlated painting and anti-correlated painting, and their painting emittance.

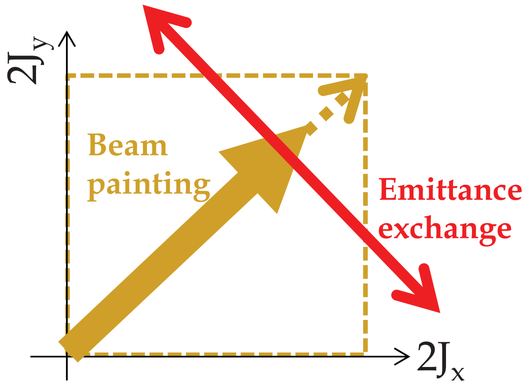
- In a situation involving the emittance exchange, investigating the particle motions while considering the geometrical relation between the beam painting and the emittance exchange in the (J_x, J_y) space is a key to optimizing the injection painting as well as to understanding the behavior of the beam.

- Based on the analysis result, the operational parameters including injection painting for the MLF and the MR were recently re-optimized, which are now successfully applied for the routine user operations.

Back-up slides

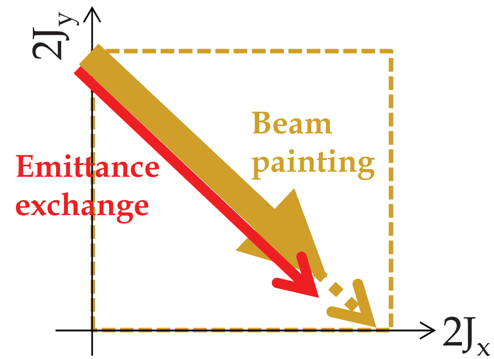
Transverse painting

◆ **Correlated painting**



$$\Delta x = x_{\max}\sqrt{t/T}$$
$$\Delta x' = -x'_{\max}\sqrt{t/T}$$
$$\Delta y = 0$$
$$\Delta y' = -y'_{\max}\sqrt{t/T}$$

◆ **Anti-Correlated painting**



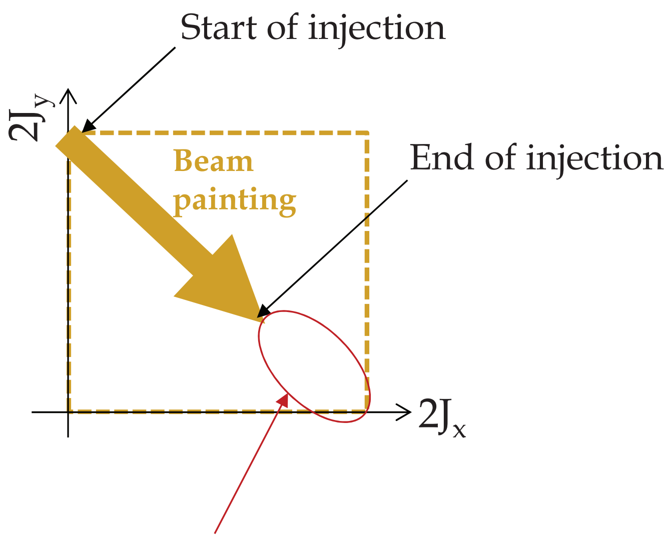
$$\Delta x = x_{\max}\sqrt{t/T}$$
$$\Delta x' = -x'_{\max}\sqrt{t/T}$$
$$\Delta y = 0$$
$$\Delta y' = -y'_{\max}\sqrt{1-t/T}$$

✓ The handling of the painting function is another promising knob for further improvement of transverse painting

Transverse painting

✓ We possibly remove a negative effect of the anti-correlated painting by handling the route of beam painting, e.g. "halfway painting".

◆ Anti-Correlated painting



$$\Delta x = x_{max}\sqrt{t/T}$$

$$\Delta x' = -x'_{max}\sqrt{t/T}$$

$$\Delta y = 0$$

$$\Delta y' = -y'_{max}\sqrt{1-t/T}$$

✓ In this empty space,
the beam is automatically distributed by the emittance exchange.

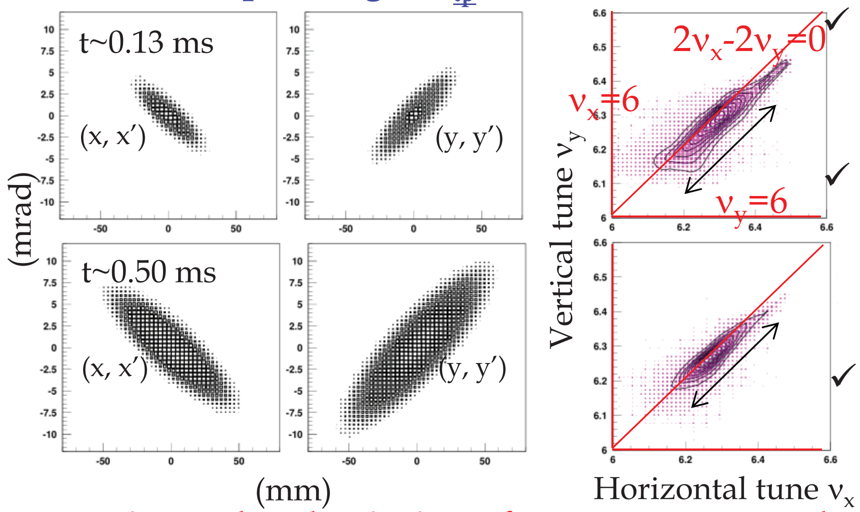
✓ This kind of halfway painting well suppresses a modulation of the charge density,
and well maintains a uniform beam distribution,
which was confirmed in the numerical simulation.

Numerical simulation

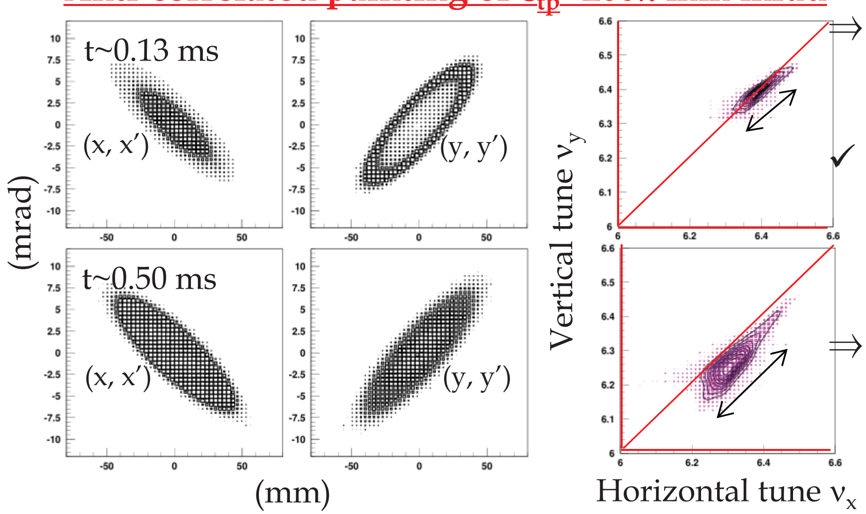
- **Simpsons** (developed by Dr. Shinji Machida)
  - PIC
  - 3-D motion of beam particles including space-charge and realistic injection process
- **Machine imperfections included:**
  - **Time independent imperfections**
    - Multipole field components for all the main magnets:
      BM ($K_{1\sim6}$), QM ($K_{5,\,9}$), and SM (K_8) obtained from field measurements
    - Measured field and alignment errors
  - **Time dependent imperfections**
    - Static leakage fields from the extraction beam line:
      $K_{0,1}$ and $SK_{0,1}$ estimated from measured COD and optical functions
    - Edge focus of the injection bump magnets:
      K_1 estimated from measured optical functions
    - Multipole field components of the injection bump magnets:
      K_2 . . . estimated from field measurements
    - BM-QM field tracking errors
      estimated from measured tune variation over acceleration
    - 1-kHz BM ripple
      estimated from measured orbit variation
    - 100-kHz ripple induced by injection bump magnets
      estimated from turn-by-turn BPM data . . . etc.
  - **Foil scattering**
    Coulomb & nuclear scattering angle distribution calculated with GEANT

Tune footprint during injection

Correlated painting of ε_{tp}=200π mm mrad



Anti-correlated painting of ε_{tp}=200π mm mrad



✓ Main source of $2\nu_x-2\nu_y=0$:
Nonlinear space-charge fields
such as octupole

✓ Correlated and anti-correlated painting
gives different strengths of
the nonlinear space-charge fields.

✓ In correlated painting,
the charge density per beam emittance
is nearly unchanging throughout
the painting process.

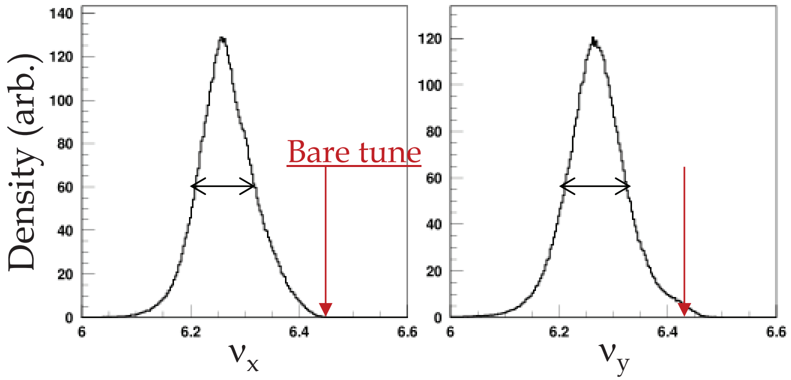
⇒ The tune footprint is almost kept
constant during injection.

✓ In anti-correlated painting,
the balance of the charge densities
on the horizontal and the vertical planes
varies during injection.

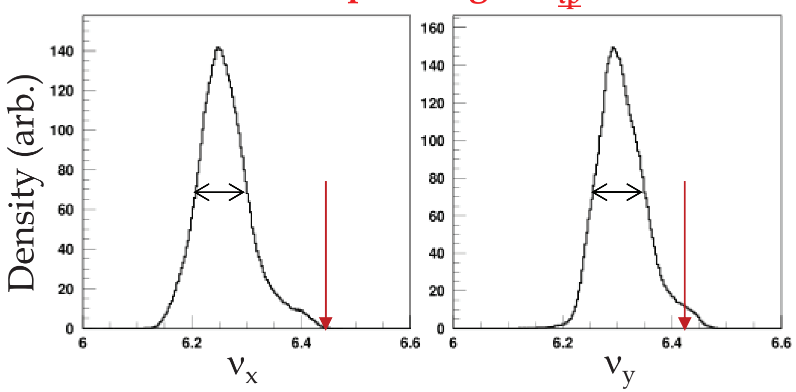
⇒ The tune shift also dynamically changes
during injection.

Incoherent tune spread at the end of injection

Correlated painting of ε_{tp}=200π mm mrad



Anti-correlated painting of ε_{tp}=200π mm mrad



- ✓ Anti-correlated painting gives narrower tune spread at all times during injection.
- ✓ This means anti-correlated painting leads to less nonlinear space charge fields.
- ✓ Anti-correlated painting is a painting scheme to form a KV-like distribution, so it serves to reduce nonlinear space charge fields.

- ✓ The activity of the emittance exchange is well mitigated for anti-correlated painting, while it is more enhanced for correlated painting.